Office of Naval Research Graduate Traineeship Award in Ocean Acoustics for Srinivasan Jagannathan

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LONG-TERM GOALS

1. Dynamics of clutter

The long term goal of this research is to develop a general method to determine the dynamics of clutter observed in sonar imagery such as Ocean Acoustic Waveguide Remote Sensing[1] (OAWRS). We aim to use waveguide remote sensing techniques to obtain time varying density images of clutter in a shallow water environment, and use these images to develop a robust technique to invert for clutter dynamics. Currently there is no robust method to determine the dynamics of clutter from density images. Our research aims to ultimately distinguish clutter from intended targets by exploiting the differences in their dynamics.

2. Clutter characterization

The long term goal of this research is to develop a Greens' Theorem-based full-field model to quantify scattering from man-made cylindrical targets in an ocean waveguide, and use the model to characterize and distinguish returns from such man-made targets from clutter such as fish schools.

3. Hurricane classification

The long term goal of this research is to analyze underwater noise measurements in the vicinity of a hurricane to help in surface wind speed estimation.

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OBJECTIVES

1. Dynamics of clutter

The primary objectives of the research are to:

- Develop a robust method to invert for the dynamics of clutter from time varying OAWRS images.

- Invert for clutter velocity fields and dynamic forces driving clutter by applying the method to sequential OAWRS images from clutter experiments conducted in continental shelf environments.

2. Clutter characterization

The primary objectives of the research are to:

- Characterize clutter in active sonar images.

- Develop and apply a Greens' theorem-based full field model to quantify acoustic scattering from man-made cylindrical targets in an ocean waveguide.

- Develop techniques to distinguish man-made targets from clutter, including fish schools.

3. Hurricane classification

The primary objectives of this research are:

- Studying the characteristics and mechanisms of underwater ambient noise in high winds including hurricane conditions.

- Determine the destructive power of hurricanes from inexpensive underwater hydrophones.

- Conduct a major oceanographic experiment to measure underwater ambient noise off Isla Socorro, Mexico, in collaboration with the Mexican Navy.

APPROACH

To invert for the dynamics of clutter, we form a minimization problem for determining the velocity and forcing fields from sequential OAWRS images obtained from acoustic clutter experiments. To test the effectiveness of the method, we use images of fish areal density distribution obtained during the OAWRS 2003 Acoustic Clutter Experiment. Current methods[3] for determining velocity fields from sequential images are specific to certain types of incompressible motion. We aim to develop a more general method that is suitable for application to clutter motion estimation that usually involves compressible motion as well.

To characterize clutter caused by both man-made targets and fish schools in continental shelf environments, we examine bistatic, long-range measurements of acoustic scattered returns from vertically extended, air-filled cylindrical targets made during three distinct field experiments in fluctuating continental shelf environments. A Greens' theorem based full-field model[4] that describes scattering from vertically extended cylindrical targets in range-dependent ocean waveguides is applied and the results are compared with field data. To account for the scintillation in the measured scattered intensity caused by fluctuations of the ocean waveguide, Monte-Carlo simulations of the scattered field are computed by implementing the full-field model in a range-dependent environment randomized by internal waves.

WORK COMPLETED

The research work in Fiscal Year 2009 was a great success in developing and applying a new, innovative Minimum Energy Flow (MEF) technique to determine velocity fields, which requires little knowledge of the mechanisms underlying the scatterer dynamics. The Minimum Energy Flow method also enables us to determine the force fields driving motion, from time varying density images formed using long range waveguide remote sensing in a continental shelf environment.

The method has significant advantages over established techniques such as Optical Flow[3]. First, it can deal with compressible motion which is a common characteristic of density images. Second, it requires little knowledge of the underlying mechanisms that drive the motion field. The method has been successfully applied[6] to data from the OAWRS 2003 Acoustic Clutter Experiment. The time varying population density data of fish groups from this experiment has been studied in detail[1]. Quantitative measures of velocity fields explaining behavioral phenomena such as (1) translation of fish groups and (2) flow of fish in hourglass patterns are shown. Pressure gradient and force fields that drive the velocity field are also calculated.

We have analyzed data from the OAWRS 2003 Acoustic Clutter Experiment[1] to demonstrate OAWRS capability to remotely sense scattering characteristics of bio-clutter and have theoretically shown how the OAWRS approach to remotely image bio-clutter can be used in a number of continental shelves around the world[12]. We have also analyzed data from the Gulf of Maine 2006 experiment[2] to quantify clutter emergence in active sonar systems and documented the diurnal variations in the spatial and temporal distribution of bio-clutter in a region with varied oceanography and bathymetry such as the Gulf of Maine.

We have successfully developed applied a new Green's Theorem-based full field model to quantify scattering from man-made cylindrical targets in range-dependent ocean waveguides. We have also successfully calibrated[5] the model with field data of acoustic scattered returns from man-made targets made during three separate ONR-sponsored experiments: the Acoustics Reconnaissance Experiment (ARE 2001), the OAWRS 2003 Acoustic Clutter Experiment, and the OAWRS 2006 Gulf of Maine Experiment.

During Fiscal Year 2009, we successfully conducted an oceanographic experiment to record underwater noise off Isla Socorro, Mexico. During this experiment, conducted in cooperation with the Mexican Navy, we deployed hydrophones off Isla Socorro, Mexico, one of the most hurricane prone regions on earth.

RESULTS

Traditional methods of motion estimation from time varying images such as Optical Flow depend on a "constant brightness assumption" where the image pixel value is assumed to be constant as the images evolve. Sonar images that describe clutter, however, usually describe underlying processes that involve deformable or compressible motion. Also, in sonar applications, we do not know the underlying principles that govern the motion observed in the images. There is thus a need to develop a general approach in dealing with inverting clutter dynamics from time varying density images.

The MEF technique that we have developed, can deal with both incompressible and compressible motion, since it employs a compressible continuity equation to describe the motion field. By using a Least Action Principle to describe the motion, we also ensure that MEF requires minimum apriori knowledge of the principles governing the motion of clutter.

We applied MEF to density images obtained from the OAWRS 2003 Acoustic Clutter Experiment[6]. Using this method we are able to use the time variation in spatial density distribution to estimate the velocity field in these images. Using the computed velocity fields we are now able to quantify the behavioral dynamics of biologically induced clutter such as fish groups over large spatial scales for the first time. We have shown[6] that (1) typically, the magnitudes of the clutter velocities are on the order of the typical fish velocities[8], (2) the major types of fish-shoal motion such as translation, coalescence, spitting, contraction and expansion can be explained by quantifying (environmental) pressures and their gradients computed using MEF. The pressures and forces acting on fish shoals is computed by modeling the fish shoal as a compressible fluid and using a Navier-Stokes equation based approach. These pressure gradients are a measure of the typical accelerations experienced by the fish groups that ultimately drive the behavior. Quantifying these dynamical quantities now enables us to model motion arising from bioclutter such as large fish shoals as well as to predict the short time span behavior of these groups ultimately enabling clutter classification.

Bistatic, long-range measurements of acoustic scattered returns from vertically extended, air-filled cylindrical targets were made during three distinct field experiments in fluctuating continental shelf environments. It is shown[5] that Sonar Equation estimates of mean target-scattered intensity lead to large errors, differing by an order of magnitude from both the measurements and waveguide scattering theory. This is because the sonar equation approximation is not applicable to targets large compared to the acoustic wavelength in an ocean waveguide. The use of the Ingenito scattering model is also shown to lead to significant errors in estimating mean target-scattered intensity in the field experiments because they were conducted in range-dependent ocean environments with large variations in sound speed structure over the depth of the targets, scenarios that violate basic assumptions of the Ingenito model. A Greens' theorem based full-field model[4] that describes scattering from vertically extended cylindrical targets in range-dependent ocean waveguides by taking into account non-uniform sound speed structure over the target's depth extent is shown to accurately describe the statistics of the targets' scattered field in all three field experiments. Furthermore, the target-scattered returns are shown to have a very different spectral dependence than that of returns from target-like clutter such as fish schools that plague long-range navy sonars operating in continental shelves, so that multi-frequency measurements can be used to distinguish fish from man-made targets.

Our analysis of active sonar data from the 2003 Geoclutter Experiment showed that the fish shoals imaged by OAWRS were stronger scatterers than theoretically predicted[12]. We also showed that OAWRS can be used in a variety of continental shelves around the world to characterize bioclutter.

Clutter emergence in active sonar system was quantified by analyzing wide-area sonar images from the 2006 Gulf of Maine Experiment[2]. The spatial and temporal distribution of bioclutter was documented over an entire diel cycle for two weeks in the Gulf of Maine. Our analysis showed that, as with the New Jersey Continental Shelf[1], fish shoals were the major cause of clutter in tactical navy sonar systems even in a region with varied bathymetry and oceanography, such as Gulf of Maine. We also showed that clutter identification and mitigation is possible through a systematic observation of its evolution over time and space.

We successfully deployed two hydrophones off Isla Socorro, Mexico, to record underwater noise. This was done in collaboration with the Mexican Navy. The hydrophones will record underwater ambient noise for a year, after which we will retrieve data recorded during that period. Early reports indicate that at least one hurricane passed directly over our sensors, which will enable us to correlate the underwater noise intensity with the high surface wind speeds associated with the hurricane. Isla Socorro was chosen because of the high frequency of hurricanes that pass by the island.

IMPACT/APPLICATIONS

Estimation of the kinematic and dynamic parameters from images is very important to predict behavior and ultimately help in classification of the different targets images using long range sonar. Man made objects tend to have a constant and predictable velocity field, whereas biologically induced clutter have more spatial variability in their velocity distribution. Minimum Energy Flow helps in identifying these trends in velocity distribution and thus helps in clutter classification.

Developing full-field scattering models to accurately predict scattering characteristics of man-made targets and bioclutter such as fish schools, directly impacts clutter mitigation and identification. For example, we show[5] that differences in acoustic frequency response of man-made, air-filled cylindrical targets and fish schools can be directly used for clutter identification. We also show the inadequacy of both the Navy-standard sonar equation and the Ingenito scattering models to accurately model the scattering from extended targets in range- and depth-dependent continental shelf waveguides.

Correlating underwater noise intensity with surface wind speed gives us a great tool to estimate wind speeds in hurricanes, without having to use sophisticated “hurricane hunting” aircraft. Earlier work by Evans et. al[9] shows the existence of a power law relationship between underwater noise intensity and the surface wind speed, at low wind speeds (<10 m/s). Recently, Wilson and Makris[10,11] have shown the existence of the same power law relationship between the underwater noise intensity and the surface wind speed, even at high wind speeds in hurricane conditions. Analyzing the underwater noise data from Isla Socorro would lend further proof to their work.

PUBLICATIONS

Journal papers

- S. Jagannathan, I. Bertsatos, D. Symonds, T. Chen, H.T. Nia, A.D. Jain, M. Andrews, Z. Gong, R.W. Nero, L. Ngor, J.M. Jech, O.R. Godø, S. Lee, P. Ratilal, N.C. Makris, “Ocean Waveguide Acoustic Remote Sensing (OAWRS) of Marine Ecosystems,” Mar. Ecol. Prog. Ser., special issue on Ocean Acoustics, 395, 137-160.

- N.C. Makris, P. Ratilal, S. Jagannathan, Z. Gong, M. Andrews, I. Bertsatos, O.R. Godø, R.W. Nero, J.M. Jech, "Critical population density triggers rapid formation of vast oceanic fish shoals," Science 323 (5922), pp 1734.
- S. Jagannathan, B. Horn, P. Ratilal and N. C. Makris, "Force estimation and prediction from time-varying density images," in press, IEEE Trans. Patt. Anal. Mach. Intell., (2010).
- S. Jagannathan, E. Küsel, P. Ratilal and N. Makris, "Scattering from extended targets in range-dependent fluctuating ocean-waveguides with clutter, from theory and experiments", to be submitted to J. Acoust. Soc. Am.
- N.C.Makris, P. Ratilal, D. Symonds, S. Jagannathan, S. Lee, R.W. Nero, "Fish population and behavior revealed by instantaneous continental shelf scale imaging," Science 311, pp 660.

Conference presentations

- S. Jagannathan, P. Ratilal, B. Horn, N.C. Makris, "Fish velocity and pressure gradient fields from acoustic flow in sonar images, with application to large fish shoals imaged by OAWRS", SEAFACTS, Bergen, Norway, 2008.
- S. Jagannathan, S. Lee, D. Symonds, P. Ratilal, N.C. Makris, "Estimating pressure gradients governing fish shoal dynamics over continental-shelf scales" J. Acoust. Soc. Am. 120, 3060, 2006.
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